PHYSICAL REVIEW C VOLUME 39, NUMBER 2 FEBRUARY 1989

Shell-model calculations of the neutron-rich ^{40}Cl nucleus

Xiangdong Ji
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

B. H. Wildenthal
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131
(Received 12 September 1988)

The low-lying spectrum of the neutron-rich doubly-odd nucleus ^{40}Cl is studied with a shell-model space consisting of all configurations of neutron and proton $0d_{3/2}$ and $0f_{7/2}$ orbitals, a space which emphasizes the effects of multiparticle-multihole excitations. The effective interaction among the valence particles was obtained from a systematic fit to the low-lying spectra of nuclei within the model space. The model predictions are compared with other shell-model calculations which emphasize spaces characterized by many orbits but only $0\hbar\omega$ configurations, as well as with the limited available experimental data.

The ^{40}Cl nucleus has six more neutrons than protons, and thus is far from the valley of stability of light nuclei. Study of this nucleus from both theoretical and experimental aspects is motivated by the general interest in testing shell-model concepts for neutron-rich or proton-rich nuclear systems. In this Brief Report, we first summarize some previous theoretical and experimental findings about ^{40}Cl and then present results of a new calculation based on a shell-model space with many-particle, many-hole excitations among the $0d_{3/2}$ and $0f_{7/2}$ single-particle orbits. Some significant differences between various theories and between experiment and theory should motivate more extended studies in both areas.

Three different experiments have been used to study the low-lying excitations of the ^{40}Cl nucleus. The study of charge-exchange reactions ^{40}Ar(^{7}Li,^{7}Be)^{40}Cl and ^{40}Ar(^{11}B,^{11}C)^{40}Cl by Fifield *et al.*[1] identified eight levels up to 2.29 MeV of excitation energy. Along with the ground state, the levels observed at 0.64, 0.84, and 1.16 MeV were strongly excited by the reactions at forward angles. If excitations to these levels occur by the pickup of a $0d_{3/2}$ proton followed or preceded by the stripping of a $0f_{7/2}$ neutron, the strongly populated states in the reaction should be made predominantly from the weak coupling of the configurations of the ^{37}Cl $\frac{3}{2}^+$ ground state and the ^{43}Ca $\frac{7}{2}^-$ ground state.

Four γ rays from the deexcitations of the ^{40}Cl excited states populated by the ^{40}S beta decay were identified by Dufour *et al.*,[2] but no level scheme was suggested in their work. In a recent experiment by Kozub *et al.*,[3] in-beam γ rays following from the heavy-ion reaction ^{9}Be(^{36}S,αp)^{40}Cl were studied by a threefold coincidence technique. A decay scheme was suggested in this study based on seven observed γ rays, some in coincidence with each other, and is shown in Fig. 1, together with tentative spin assignments for some of the levels. The preliminary angular distribution data indicate that the 238 and 357 keV γ-ray transitions are of the stretched dipole type.[3]

The first shell-model calculation for the level scheme of ^{40}Cl was done by Woods,[4] based on a shell-model space of valence $1s_{1/2}$ and $0d_{3/2}$ neutron orbitals and valence $0f_{7/2}$ and $1p_{3/2}$ proton orbitals. No valence particles were allowed to be excited from one major harmonic oscillator shell to another. The effective Hamiltonian in the $1s0d$ subspace was Wildenthal's universal $1s0d$ (USD) interaction[5] and that in $0f1p$ subspace was taken from Gloeckner's work.[6] The $1s0d$-$0f1p$ cross-shell matrix elements were taken from the work of Schiffer and True.[7] The level predictions of Woods are presented in Fig. 1.

Recently this same general approach was employed by Warburton *et al.*[8] with an enlarged shell-model space and a different interaction. In Warburton's calculation, the protons are allowed to move in the full $1s0d$ shell and neutrons to move in the full $0f1p$ shell. The proton $1s0d$ shell elements were again taken from the work of Wildenthal,[5] the matrix elements in the $0f1p$ shell were taken from the work of McGrory,[9] and the cross-shell matrix elements were taken from the work of Millener and Kurath.[10] The predictions of this model are also presented in Fig. 1. A one-to-one correspondence between levels from Woods's-and Warburton's calculations can be

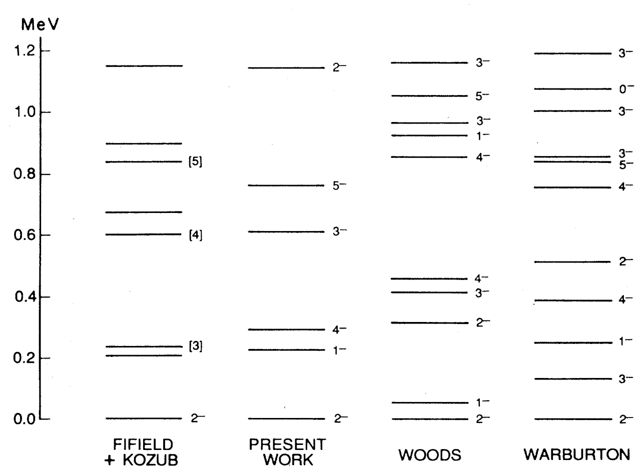

FIG. 1. Comparison of the experimental and theoretical level schemes for the neutron-rich ^{40}Cl nucleus.

made, but the ordering of levels is quite different.

The two shell-model calculations described above forbid any particle-hole excitations between major shells, although they allow the valence protons and neutrons to move among the several subshells of the corresponding major shells. In the shell-model calculation we present below, a quite different approach is taken, namely the valence neutrons and protons are confined to a two-orbit model space, and all $2\hbar\omega$, $4\hbar\omega$, etc. excitations within this limited orbital model space are included.

Our shell-model calculation is based on a study[11] which modeled states of $A=33-48$ nuclei in terms of $A-32$ particles distributed without restriction over the $0d_{3/2}$ and $0f_{7/2}$ orbits. Given the technology for constructing and diagonalizing shell-model matrices, all that is needed to generate predictions for level energies and wave functions from an assumed orbit space is the set of one-body and two-body energies for these orbits. Our study commenced by taking as the single-particle energies for the $0d_{3/2}$ and $0f_{7/2}$ orbits the binding energies relative to ^{32}S of the lowest $\frac{3}{2}^+$ and $\frac{7}{2}^-$ levels of ^{33}S. There are 24 two-body matrix elements in the $0d_{3/2}$-$0f_{7/2}$ orbit space. We took as initial values for the 20 diagonal two-body matrix elements the mass-averaged results of Daehnick.[12] We use the values of Ref. 13 for the four off-diagonal matrix elements.

With this initial input, we constructed and diagonalized matrices for 150 states in the $A=33-48$ region, concentrating on ground, low-lying and stretched levels. The shell-model eigenvalues obtained in these diagonalizations should, if our assumption is valid, correspond to experimentally observed nuclear levels in this region. Such correspondences do emerge quite clearly when the theoretical and experimental spectra for the various nuclei are compared. The values of the 26 Hamiltonian parameters were then adjusted through two iteration cycles with the technique of Ref. 14 to obtain values for this space which provide better agreement with the selected set of level-energy data. With the model space and model Hamiltonian described, we have generated predictions for the neutron-rich nucleus ^{40}Cl and present the energy levels up to 1.25 MeV of excitation in Fig. 1, along with results of the other two calculations previously mentioned.

The spin-parity of the ground state of ^{40}Cl is predicted to be 2^- by all calculations, a prediction which is verified experimentally from its β decay to ^{40}Ar. The ground-state energy is calculated in our model to be 337,379 keV, in good agreement with the experimental value of 337,090$\pm$500 keV. The ground-state wave function in our model calculation contains 83% $0\hbar\omega$ configurations, 56% of which belong to the seniority-two component. The predominant $2\hbar\omega$ configuration is the two-neutron excitation to the $0f_{7/2}$ orbit, with a probability of 13%. The ground-state neutron occupation in the $0d_{3/2}$ orbit is thus 3.68, whereas the proton occupation in the $0f_{7/2}$ orbit is very small, only 0.03.

The first excited state in our calculation is 1^-, and lies 232 keV above the ground state. Woods also predicts 1^- as the first excited state, but with an excitation energy of only 64 keV. On the other hand, Warburton predicts the first excited state to have spin-parity 3^-. The first 1^- state in Warburton's calculation is at 253 keV, a value very close to ours. In our model, this 1^- state is made from the coupling of the $0d_{3/2}$ proton with the first excited $\frac{5}{2}^-$ state of ^{43}Ca, which is a seniority-three $0f^3_{7/2}$ state. (On the basis of experimental evidence, this state is not an $f_{5/2}$ single-particle state, as was suggested in Ref. 3.) Thus this state should not be seen in the single-charge-exchange reactions. It can, however, decay to the 2^- ground state by emitting an $M1$ γ ray. Thus, it is possible to identify this state as the 212 keV state observed in the in-beam γ-ray experiment.

The weak peak around 240 keV seen in the charge-exchange reaction probably corresponds to the state identified at 244 keV in Ref. 3, where it was assigned a spin-parity of 3^-. The structure of the state is not likely to have a $0d_{3/2}$-$1p_{3/2}$ structure, because the single-particle $1p_{3/2}$ state in ^{43}Ca is relatively high (around 2 MeV); on the other hand, it also should not be the coupling of $0d_{3/2}$ to the first $\frac{3}{2}^-$ state in ^{43}Ca (593 keV) either, since otherwise it should not be seen from the charge-exchange reaction.

In our model calculation, we predict a 4^- state at 298 keV, which is a coherent mixture of $0d_{3/2}\otimes(\frac{7}{2}^-)_1(^{43}\mathrm{Ca})$ and $0d_{3/2}\otimes(\frac{5}{2}^-)_1(^{43}\mathrm{Ca})$ configurations, with each accounting for about 40% of the total. If we identify this state as the 244 keV level, then the transition to the ground state would be $E2$ rather than $M1$. However, the 4^- state in ^{38}Cl is predicted too low by 324 keV in our model; if a similar discrepancy occurs in ^{40}Cl, then the state at 244 keV might be an intruder relative to our model. The first 3^- states predicted in both the Warburton and the Woods calculations are possible theoretical candidates for this 244 keV level, but to confirm this, excitation strength in the charge-exchange reaction should be calculated and compared to the experiment.

The state at 601 keV observed in the in-beam γ-ray experiment makes an $M1$ transition to the state at 244 keV and also a crossover transition to the ground state; thus its spin-parity can be 2^-, 3^-, and 4^-. Our calculation favors the 3^- assignment, with the theoretical excitation energy at 612 keV. A large charge-exchange excitation strength for this state is predicted, which might correspond to the peak observed at 640 keV in Fifield's experiment. This same state could, on the other hand, also be 4^- if the state at 244 keV is 3^-, as both Warburton's and Woods's shell-model calculations suggest.

The state observed at 840 keV in the charge-exchange reaction probably corresponds to the 839 keV state suggested in Ref. 3. From its decay to the level at 601 keV, Ref. 3 assigned its spin-parity as 5^-. This state can be identified as the first 5^- state in our model calculation, and is also predicted in the other two shell-model calculations. Since our model wave function for the state indicates that it belongs to the $0d_{3/2}\otimes 0f_{7/2}$ multiplet, it is consistent with experimental evidence that the state is excited strongly in the charge-exchange reaction. The experimentally observed charge-exchange strength at 1160 keV can be associated with the second 2^- and 4^- states of our model results. These states carry about 20% of the $0d_{3/2}$-$0f_{7/2}$ strength.

There are two more states observed experimentally than are produced by our model calculations below 1.0 MeV. They should not be observed in the charge-exchange experiment, as they are not included in our model space. More states are predicted by the other two shell-model calculations in this region. Identification of these states with the states populated in the γ-ray experiment is difficult without more experimental information other than excitation energy.

In conclusion, the several current shell-model calculations agree in predicting the spin-parity assignments for the ground state of ^{40}Cl and for the 5^- level around 840 keV. The identification of other members of the simple $0d_{3/2}$-$0f_{7/2}$ multiplet states with the levels observed at 230 and 640 keV in the charge-exchange reaction experiment is not clear. The situation can be improved by pushing the current calculations to the next level of completeness and consistency. In particular, the role played by the $1s_{3/2}$ and $1p_{3/2}$ orbits omitted in our calculations is as important as the multiparticle-multihole excitations. Many low-lying states with excitations and occupations of these orbitals were observed in the calculations of Refs. 4 and 8. These states are energetically favorable to mix with the $0d_{3/2}$-$0f_{7/2}$ multiplet. The two-particle–two-hole states examined in the present calculation are typically at 3 MeV of excitations. The sensitivity of the energies and wave functions of the $0d_{3/2}$-$0f_{7/2}$ multiplet to these particle-hole configurations points out the necessity of including them in calculations. Therefore, a better calculation should have a model space, which includes the important $1s0d$ and $0f1p$ subshells and the cross-shell excitations, and a Hamiltonian, which reproduces many other experiments in the same nuclear region. Finally, consolidation of the present experimental information is needed to clarify the number of levels below 1.2 MeV and some of their J^{π} assignments.

We thank Dr. E. K. Warburton who provided us with his shell-model results. This work was supported by National Science Foundation (NSF) Grants PHY87-18772, PHY86-04197, and PHY85-05682.

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